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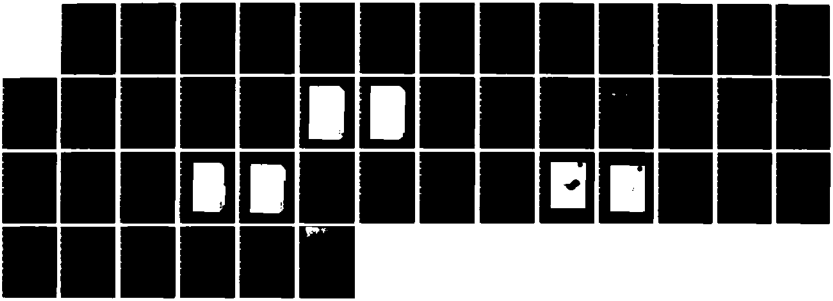

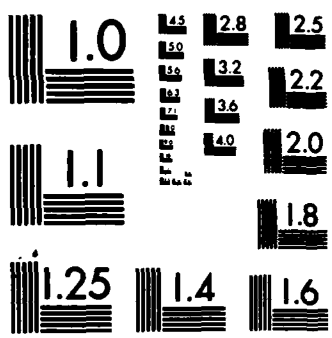

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DETERMINATION OF STRATOSPHERIC WIND PROFILES BY DIGITAL ANALYSIS

Christian A. Trowbridge

PhotoMetrics, Inc.
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4 January 1984

Final Report for Period 14 August 1981 - 13 August 1983

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PREPARED FOR

AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A program to measure altitude profiles of the horizontal wind velocity in the stratosphere using smoke trail tracers is described. The system for accessing and digitizing photographs of the sunlight scattering trails was updated with new hardware and software. Film plane coordinates of trail center lines were identified by computer programs, and vector triangulation

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20. Abstract (continued)

was applied to determine three-dimensional coordinates of the trail. Highly accurate camera orientations were obtained for input to the triangulation procedure by digitizing images of known stars. Time sequences of positions of points on the trail centerline were then processed to determine the horizontal wind field and its vertical shears.

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FOREWORD

The program described here involved the operation, maintenance, and upgrade of the AFGL Trail Digitization System at PhotoMetrics, Inc., for computer access of photographic records of atmospheric smoke and chemical trails. Subsequent computer analysis of triangulation image pairs was performed to determine trail positions, from which horizontal wind components and wind shears were calculated.

Earlier work by PhotoMetrics on analysis of stratospheric smoke trails is reported in Ref's 2 and 5, and the video densitometer system for measuring trail coordinates is described in Ref 1. Major improvements of both the computer hardware and software were implemented at the beginning of the current program.

The author wishes to express thanks to Dr. A.F. Quesada (Technical Monitor) of Air Force Geophysics Laboratory for his continued encouragement and support, and to K. McDevitt and C. Rice of PhotoMetrics for their contributions to this report.

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SECTION I

SUMMARY AND OVERVIEW

The objective of the work reported here is to measure stratospheric wind velocities by precision photographic triangulation of tracer smoke trails released from sounding rockets. Trail images were first reduced to digital form using the AFGL's Trail Digitization System (Ref 1) which provides semi-automatic alignment of each film frame (to establish the film plane coordinate system coincident with the camera film plane and optic axis) and measures the position of the centerline. The trail was then located by triangulation from pairs of images taken from spatially-separated remote measurement sites, and winds and shears were derived from its positions (Ref 2).

A brief review of the smoke trail triangulation technique is presented in Section II, which references the development of the vector methods currently employed. A summary of data analyzed by these methods and of the problems encountered is also presented in Section II.

An extensive modification of the Trail Digitization System is detailed in Section III, and routine (as well as unscheduled) maintenance procedures discussed. Section IV reports the program's conclusions and recommendations.

SECTION II

DATA ANALYSIS

The method for determining trail position and wind fields from photographs of smoke trails released in the stratosphere is described here. Further information about the procedures may be found in Ref's 1-4. This Section also summarizes the data sets reduced and analyzed.

SMOKE TRAIL TECHNIQUE

Although the rocket deposited smoke trail technique has been utilized for over 20 years to trace atmospheric wind speed and direction, its practical, accurate, and reliable application is relatively recent. The formulation of vector methods of solution for photogrammetric triangulation to continuously released trails -- which lack features that can be unambiguously identified from multiple projections -- took place about 10 years ago (Ref 3) and improvements in determining the orientation of triangulation cameras somewhat later (Ref 4). These advances removed the problems associated with earlier plane-earth solutions or solutions employing spherical geometry. References 1,2, and 7, the first application of these methods, show that even when applying vector solutions numerous pitfalls must be avoided.

Briefly, the dense tracer smoke remains substantially intact after its release while being transported by the wind field for periods of one to two minutes. During this time synchronized cameras at a minimum of two observation sites record the projections of the trail, whose contrast against the sky results from its great scattering of sunlight (much like the contrails of aircraft). Pairs of simultaneous images are digitized to determine the coordinates in the film plane of the center line of the trail, and digital data are then used to triangulate its spatial locations. Transport of the trail in subsequent frames is used to calculate horizontal wind as a function of altitude.

To achieve positional accuracy for geophysical investigations requires that several parameters relating to camera location and orientation be known to high precision. Camera location (latitude, longitude, and altitude) are found from surveys of the site. The importance of accurate site location for determining altitude (and position) at the release cloud cannot be overemphasized. Tests on trail 12 Sep 78 (Ft. Churchill, Canada) were required to isolate the reason for inconsistent positional results from the triangulation. Multiple reductions of the trail data and analysis of the Canadian Survey data eventually determined that both site positions were incorrect. The process of isolating such an error from the triangulation results is imprecise and can only suggest where corrections may be required -- actual corrections must be made from knowledge of the survey data. Furthermore, the time (i.e., cost) of reducing such data is increased by up to an order of magnitude.

The three-axis orientation of the camera is obtained from a photograph of the star field at a precisely known time. Locations of images of known stars are digitized, and vector methods of Ref 4 are applied to relate their right ascension and declination to the digital film plane positions for determining the precise azimuth, elevation, and tilt about the horizontal of the camera. The actual focal length of the lens is also measured from these data. The number (n) of stars used provides $n(n-1)/2$ estimates of orientation angles and $n(n-1)(n-2)/6$ estimates of focal length. Precision of the average of these determinations is improved by editing out those measurements whose deviation from the mean exceeds a preselected fraction of the ensemble standard deviation (this is of course a commonly-applied procedure). Typically, standard deviations of 0.005° (azimuth and elevation), 0.01° (horizonal tilt), and 0.005 cm (focal length) are routinely achieved when using 12 or more star images.

Camera location and orientation are then input to the triangulation routine along with the position of the trail centerline as viewed from two sites. This centerline is determined by computer from a line scan across that trail, made by moving the film on a precision automatic stage through a fixed central area of the video densitometer section of the trail digitization system (to maintain constant photometric response to the film's optical density). The vector methods of Ref 3 have been formulated using an iterative approach to determine the minimum error pairing of trail points of one site with those of the other. (Recall that the situation differs from that of standard triangulation in that the trail has no recognizable "pickup points.") The primary matching criterion is minimization of the dihedral angular mismatch between planes generated by film plane point line of sight vectors for each site and the line joining the two sites. As each optimum match is found, the altitude, latitude and longitude of the intersection (or point of closest approach) of the line of sight vectors is recorded for later use in measuring the wind field.

These horizontal velocity determinations are made using a time sequence of typically five or six trail point positions, over a period of one to two minutes. Each of the position files is either spline or cubic interpolated to equal altitude increments (typically 10 m), and a least-squares analysis of position versus time provides the average horizontal velocity components and their associated experimental uncertainty. The wind velocity data routinely provide measurements of the horizontal wind's vertical shear. Further analysis may be performed (Ref's 6-8) to determine descriptors of turbulence such as length scales, heating rates, and Richardson numbers. References 4-12 are conference presentations of the results of this program and of further analyses of the wind profiles by AFGL scientists.

RESULTS

Each of the stratospheric trails which was reduced to digital form is summarized in Table 1. Included in this table is a high altitude chemical trail (in connection with AFGL's Auroral-E Experiment, ~80-140 km), which we also analyzed. Alignment of each photographic frame on the Trail Digitization System was accomplished to better than ±8 μm over an image dimension of 115 mm, with the position of the optic axis located with a repeatability of ±8 μm. For the Auroral E data (POKER, ELLIOT, recorded on 70 mm film with 55 mm image size), the optic axis was located to ±12 μm. The maximum scanning increment along the trail axis was 48 μm at low altitudes; this step was reduced at higher altitudes to preserve a nearly uniform increment in altitude from point to point in defining the wind profile.

Star-position calibrations were also digitized and analyzed for all of the trails, as summarized in Table 2. Large numbers of calibrations (for each triangulation frame) were performed for Auroral E (POKER and ELLIOT sites) because the camera orientations were frequently changed. The majority of star calibrations were reduced using new software, originally developed for another application which semiautomatically

Table 1. Summary of Data Digitized

Event Name or Date	Frame	Site	Data
NIOBE 13 Jun 75	12	SEEHORN	DASHED TRAIL
	13		
	14		
	15		
	16		
	17		
	18		
	12	TWO BUTTES	
	13		
	14		
	15		
	16		
	17		
	18		
	12	CAL	
	13		
	14		
	15		
	16		
	17		
	18		
OPS 13 Jun 75	72	TWO BUTTES	DASHED TRAIL
	73		
	74		
	75		
	76		
	72	CAL	
	73		
	74		
	75		
	76		
PANDORA 17 Jun 75	83	SEEHORN	DASHED TRAIL
	84		
	85		
	86		
	87		
	88		
	89		
	91		

Table 1. Summary of Data Digitized (continued)

Event Name or Date	Frame	Site	Data
PANDORA (cont'd)	83	CAL	
	84		
	85		
	86		
	87		
	88		
	89		
	91		
(NO NAME) 26 Apr 77	23	TWO BUTTES	DASHED TRAIL
	24		
	25		
	26		
	27		
	28		
	23	T5	
	24		
	25		
	26		
	27		
	28		
(NO NAME) 02 May 77	32	TWO BUTTES	DASHED TRAIL
	33		
	34		
	35		
	36		
	32	T5	
	33		
	34		
	35		
	36		

Table 1. Summary of Data Digitized (continued)

Event Name or Date	Frame	Site	Data
(NO NAME)	72	OBSERVATORY	DASHED TRAIL
13 Sep 78	73		
	74		
	75		
	76		
	77		
	78		
	79		
	80		
	72	TWIN LAKES	
	73		
	74		
	75		
	76		
	77		
	78		
	79		
	80		
AURORAL E	747	CHENA	HIGH ALTITUDE TRAIL
03 Mar 81	762		
	777		
	792		
	807		
	822		
	747	CENTRAL	
	762		
	777		
	792		
	807		
	822		
	40	POKER	
	41		
	42		
	43		
	50		
	60		
	70		
	80		

Table 1. Summary of Data Digitized (concluded)

Event Name or Date	Frame	Site	Data
AURORAL E (cont'd)	40	ELIOT	
	41		
	42		
	43		
	50		
	60		
	70		
	80		
AURORAL E 03 Mar 81 SPECIALLY MADE FILM COPIES	50	POKER	HIGH ALTITUDE TRAIL
	60		
	70		
	50	ELLIOT	
	60		
	70		

Table 2. Summary of Star Frames Digitized

Event Name or Date	Frame	Site	Maximum Uncertainty
NIOBE	10	SEEHORN	±8μm
13 Jun 75	9	TWO BUTTES	±8μm
	9	CAL	±8μm
OPS	80	TWO BUTTES	±8μm
13 Jun 75	30	CAL	±8μm
PANDORA	81	SEEHORN	±8μm
17 Jun 75	81	CAL	±8μm
26 Apr 77	20	TWO BUTTES	±12μm
	20	T5	±12μm
02 May 77	30	TWO BUTTES	±8μm
	30	T5	±8μm
12 Sep 78	10	TWIN LAKES	±20μm
13 Sep 78	70	OBSERVATORY	±12μm
	70	TWIN LAKES	±12μm
AURORAL E	40	POKER	
03 Mar 81	41		
	43		
	50		±12μm
	60		
	80		
	50 (copy)		
	60 (copy)		
	70 (copy)		
	40	ELLIOT	
	41		
	42		
	43		
	50		±12μm
	60		
	70		
	80		
	50 (copy)		
	60 (copy)		
	70 (copy)		

Figure 1. Triangulation photograph of trail 13 Sep 1978 taken from Observatory site (Ft. Churchill) at T = 128 Sec after rocket launch. Note fiducial markers used for alignment.

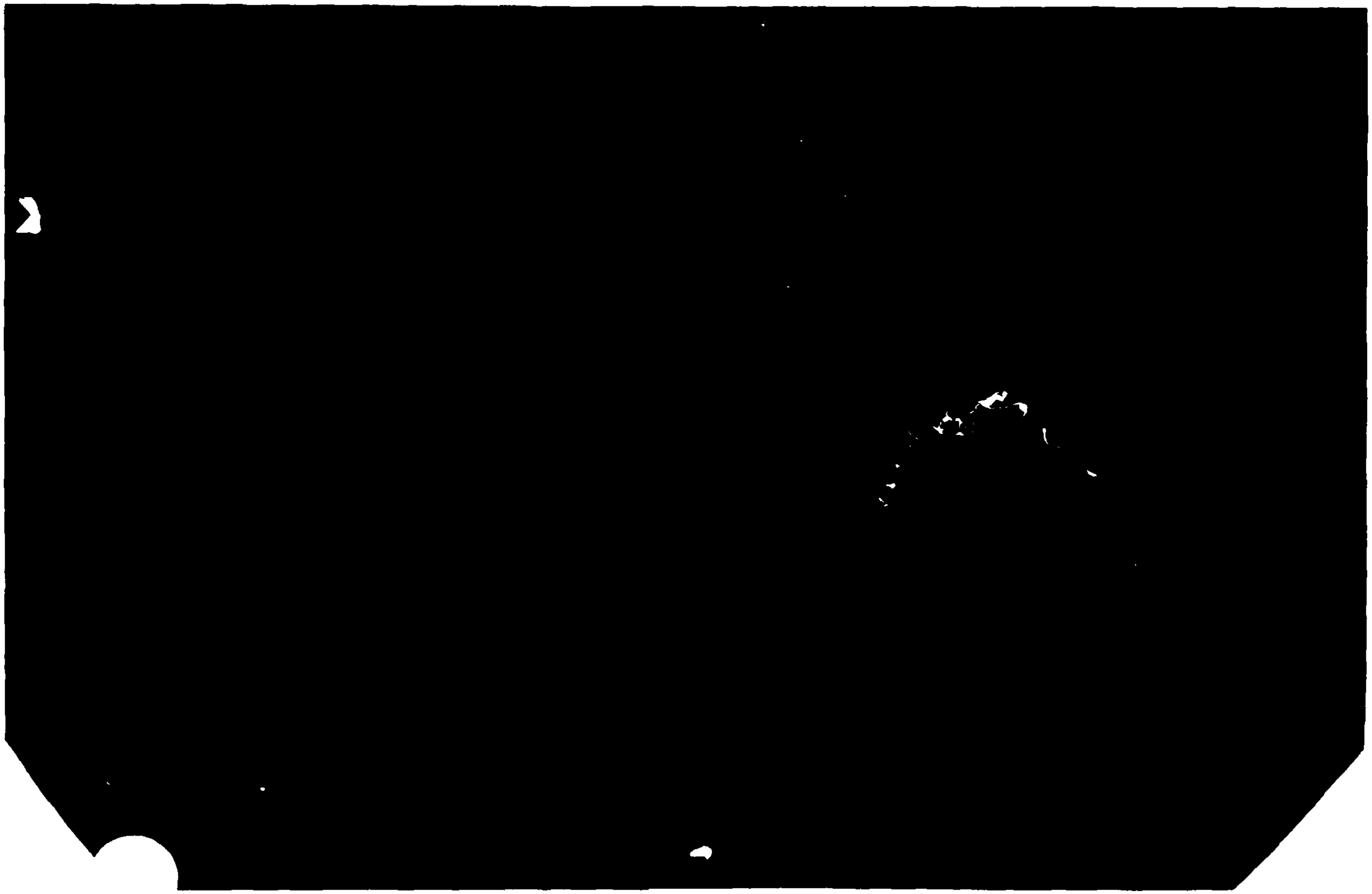

Figure 2. Triangulation photograph of trail 13 Sep 78 taken from Twin Lakes site at t = 128 sec after rocket launch.

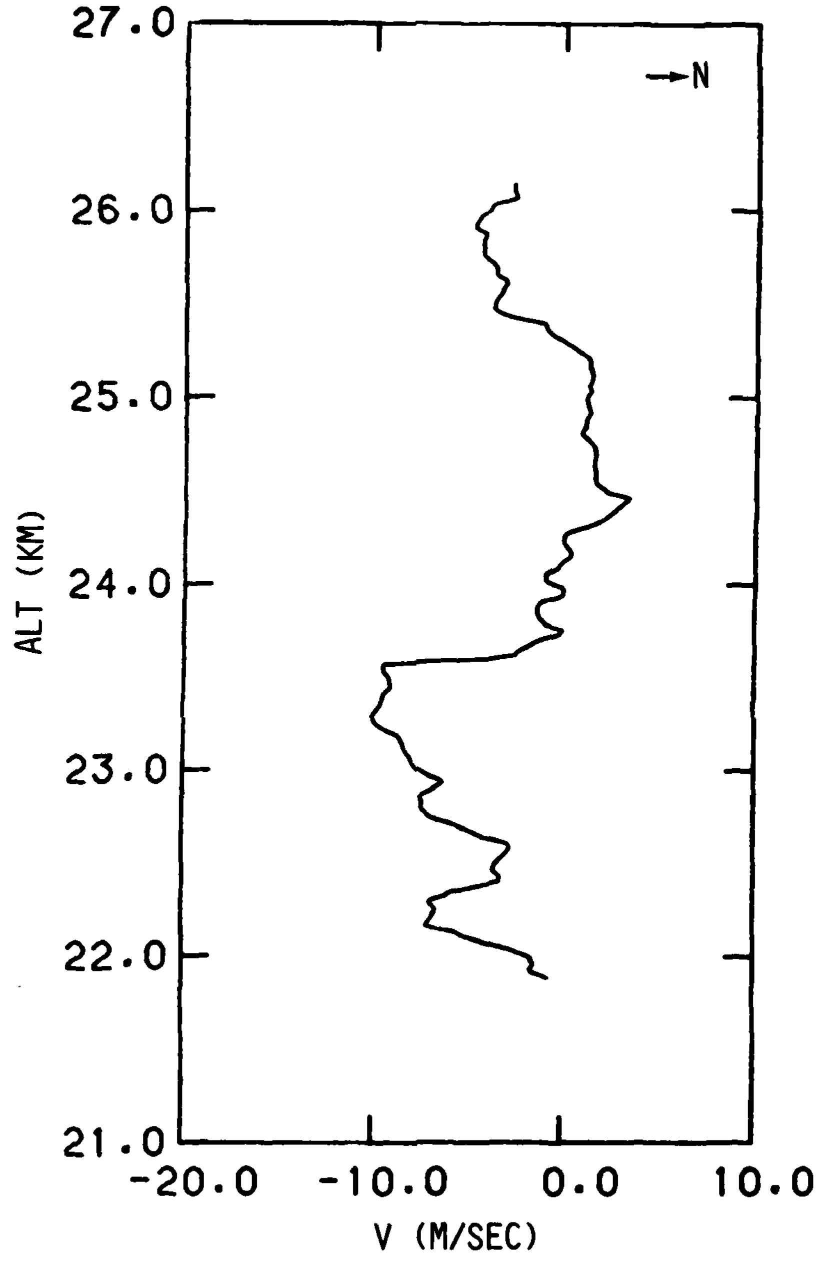

Figure 3. Northerly component of wind velocity determined from trail 13 Sep 78, Dash 2 at 10 meter altitude resolution.

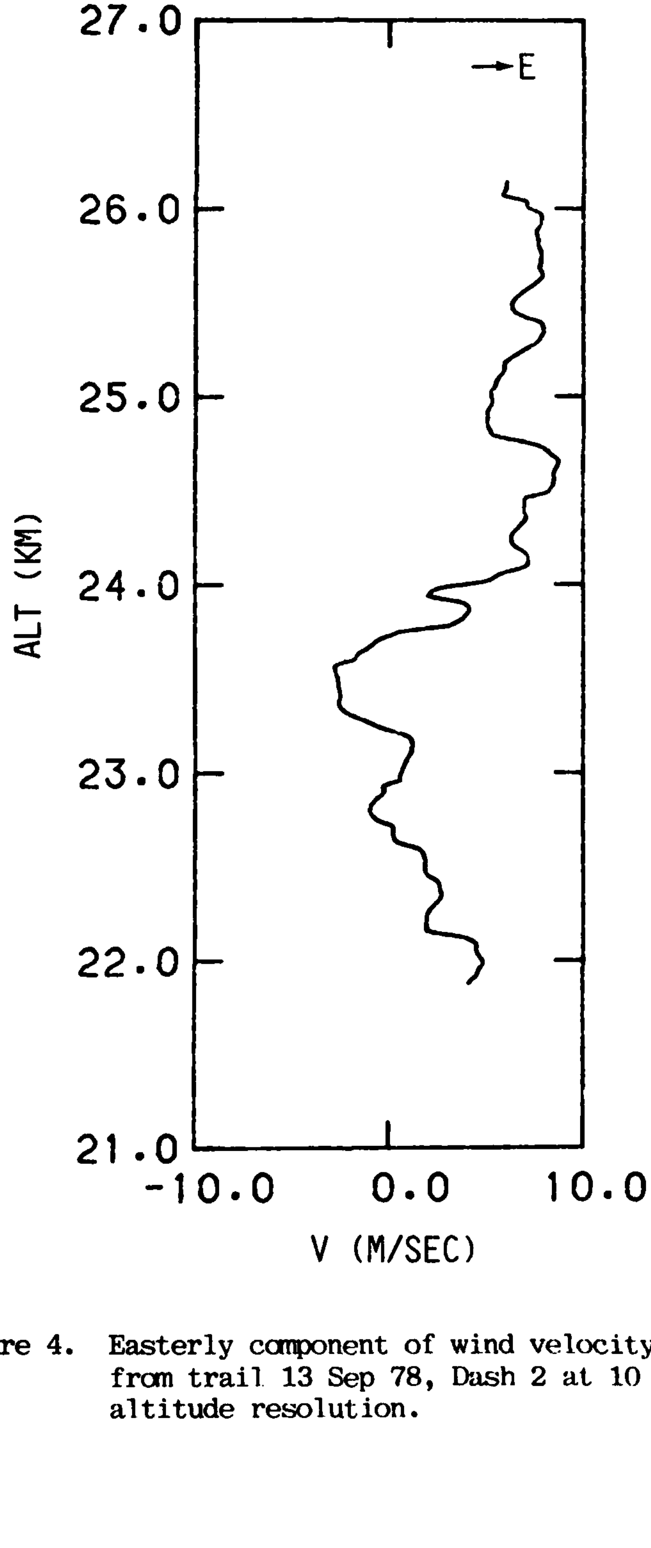

Figure 4. Easterly component of wind velocity determined from trail 13 Sep 78, Dash 2 at 10 meter altitude resolution.

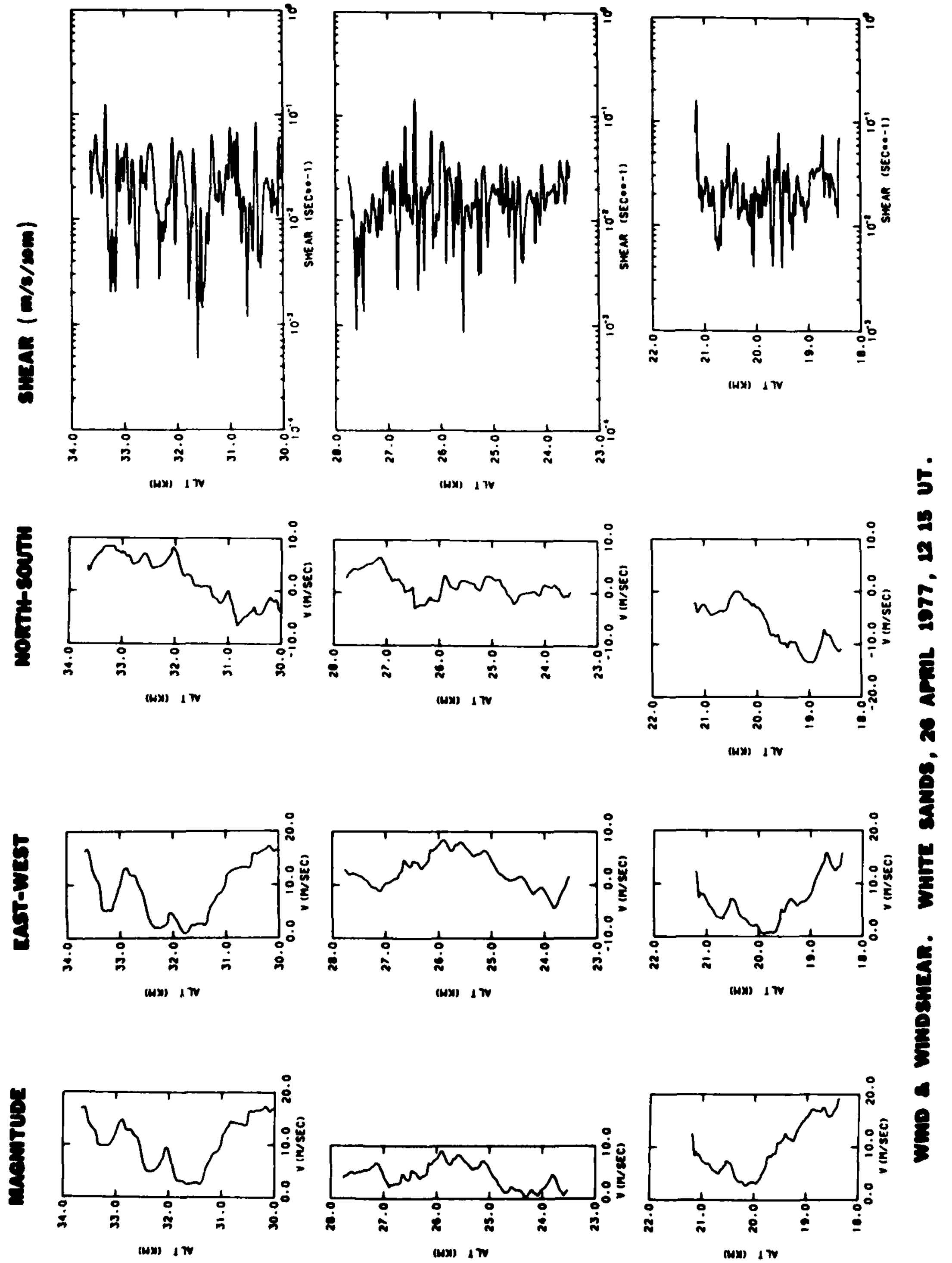

Figure 5. Wind and wind shears at White Sands, New Mexico, calculated from smoke trail released on 26 April 1977.

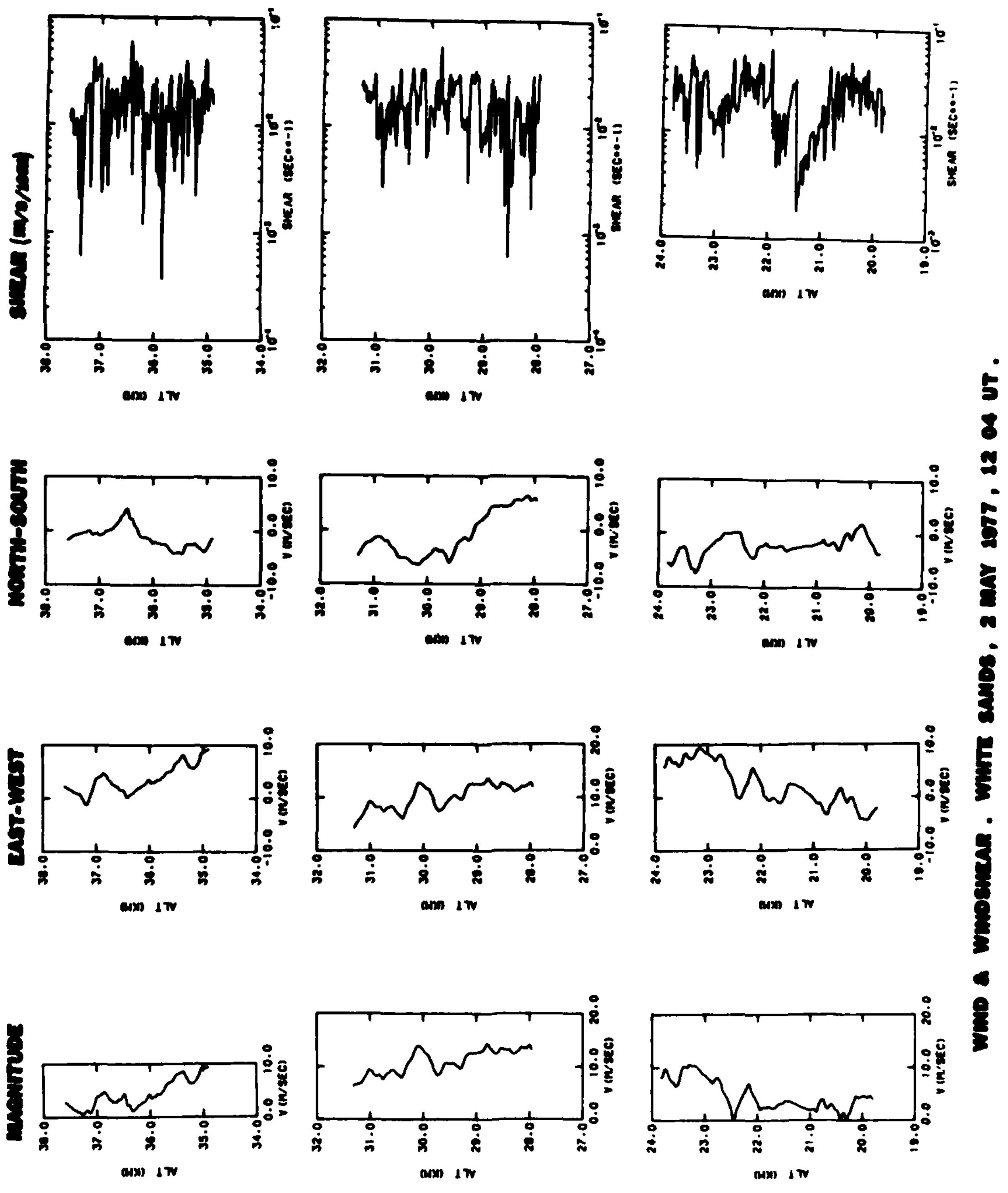

Figure 6. Wind and wind shears at White Sands, New Mexico, calculated from smoke trail released on 2 May 1977.

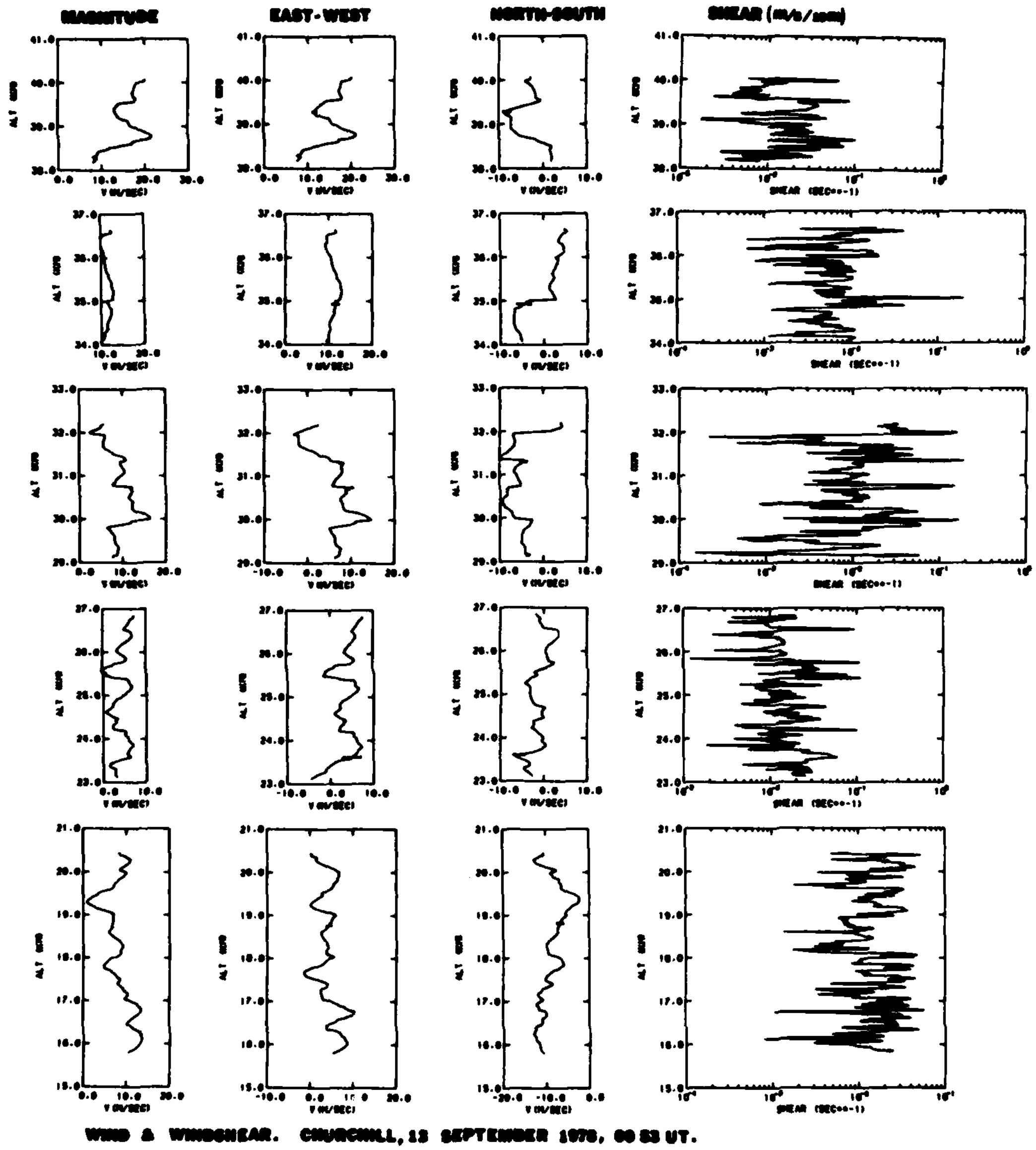

Figure 7. Wind and wind shears at Ft. Churchill, Manitoba, Calculated from smoke trail released on 13 Sept 1978.

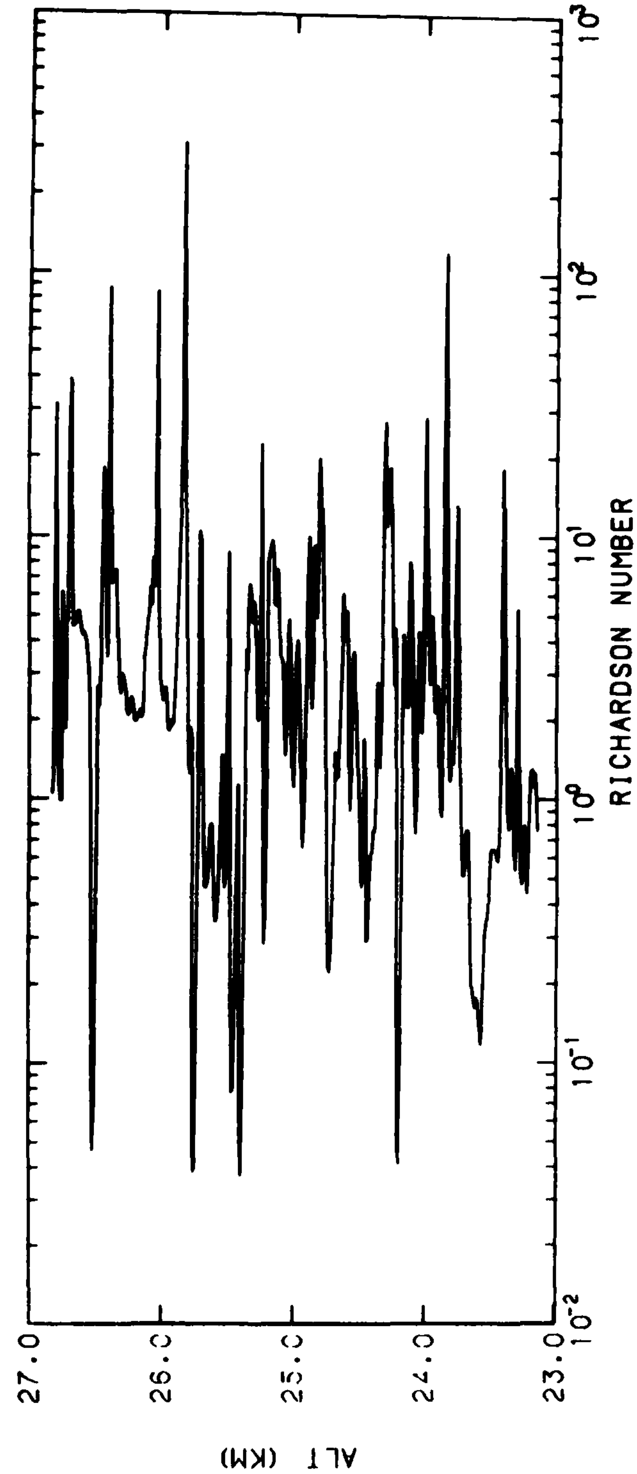

Figure 8. Richardson number profile for one dash of trail 12 Sep 78 from analysis of vertical shear of the horizontal wind and temperature measurements made from meteorological sounding rockets.

identifies the star images by means of a digital star catalog and automatically determines the film plane coordinates. Elimination of the manual identification of stars and entry of right ascension and declination has significantly reduced the time required to determine camera orientations. Repeatability of the star digitization was generally less than $\pm 8\mu m$ in both the x and y axes.

The data presented in this report are intended only to be illustrative of the analysis results which were communicated to AFGL scientists as they were obtained. Hard copy listings, computer plots, and magnetic tapes with digital information were furnished and presently reside with the LKD Branch of AFGL.

Stratospheric Trails

Each of the stratospheric trails consisted of up to 10 smoke release segments each approximately 5 km long separated by gaps of approximately 3 km. In several cases the higher altitude trail segments were near or after rocket apogee and thus spanned a very limited altitude range. Good coverage by both triangulation cameras was usually obtained from approximately 18 to 36 km altitude.

Data typical of that reduced are shown in Figures 1-8. Figures 1 and 2 are a triangulation photograph pair for release 9/13/78 taken from Observatory and Twin Lakes sites respectively. The northerly and easterly components of the wind field for dash 2 of the trail (22 to 26 km altitude) determined from a time sequence of position data, are shown in Figures 3 and 4. Wind and shear results (Ref 9) for trails 26 Apr 77, 2 May 77 and 13 Sep 78 are shown in Figures 5-7. In addition to triangulation and velocity measurements for the data listed in Table 1, previously digitized data for release 12 Sep 78 were reduced, and modified (20 m resolution) wind and shear profiles produced for trails 22 Apr 77, 20 May 78 and 22 May 78 were also calculated. Richardson numbers of turbulence were determined from the wind and temperature profiles for trails 12 Sep 78 and 13 Sep 78, an example of which is presented in Figure 8. Note that this segment of the 12 Sept 78 trail displays little turbulence (generally taken as $R_i < 1/4$) while about 95% of the data indicates that the atmosphere is stable ($R_i > 1/4$) in this region.

Auroral E Trail

The Auroral E trail (Poker Flat, AK) provided both a good test of the digitization-triangulation routines at altitudes well above the stratosphere and an example of data that are not suitable for analysis by these (or other) methods. The data set taken by AFGL from the CHENA and CENTRAL sites provided excellent wind field results from 102 to 136 km altitude and was limited only by the spatial coverage of the camera field. Figures 9 and 10 show one of the sequence of photographic pairs used for triangulation and velocity determination. Figures 11-14 are the resulting wind field (Ref 10) and shears derived from this rocket program.

In contrast to the good results from the AFGL films, images from the closely-spaced Poker Flat User Optical Site (POKER) and ELLIOT highway site cameras would not provide realistic triangulation or velocity results despite the several attempts made to reduce them. Analysis of this data set was undertaken because it would allow extension of the wind profile downward to approximately 75 km altitude. These films had been exposed as a test of a remotely operated camera system (by the University of Alaska), and were not specifically intended to be used for triangulation in view of the small

(~10 km) site separation relative to the range to the trail. Triangulation from sites placed in such close proximity can provide fairly good transverse positioning of (trails) near the stations' zenith but insufficiently accurate range (i.e., altitude) resolution. Further uncertainties result from errors in location of the sites and overexposure (saturation) of the film images of the trail.

Site location errors have been occasionally noted during previous reduction of stratospheric trails, in which errors in camera position as small as 20 m have been found to significantly alter triangulation results (and subsequent wind calculations). It is estimated that the maximum tolerable error for this (University of Alaska) Auroral E data is approximately 40 m; in contrast the final estimates of the site position accuracy are 10 m for POKER and 100 to 200 m for ELLIOT.

The lower altitude region (~75 to 100 km) this down-leg-released trail was of greatest interest consisted of a large reentry bag for this downleg released trail (Figure 15). Data acquired by the usual digitizing routines that determine the trail centerline by analysis of the film density distribution transverse to the trail axis provided poor triangulation results. A series of overlays of photographic prints, digitally-determined trail center position, and center of what could be identified as the "core" of the reentry bag was prepared; these demonstrated that the center of the bag and the somewhat higher film density core of the trail were not coincident. A set of carefully prepared contact printed film copies (Figure 16) was then made and each was subjectively marked with a line to emphasize the core, which was of too low contrast for the digitizer to follow. Triangulation using the manually identified core showed improvement over the previous automatic "bag" triangulation, but trail and altitude positions remained physically inconsistent. It appears that the combination of site location inaccuracy and small separation is responsible for these poor results. Triangulation to the "core" which is readily identifiable in contrast enhanced photographic prints, should have provided accurate and self-consistent position information in the absence of these unresolvable problems.

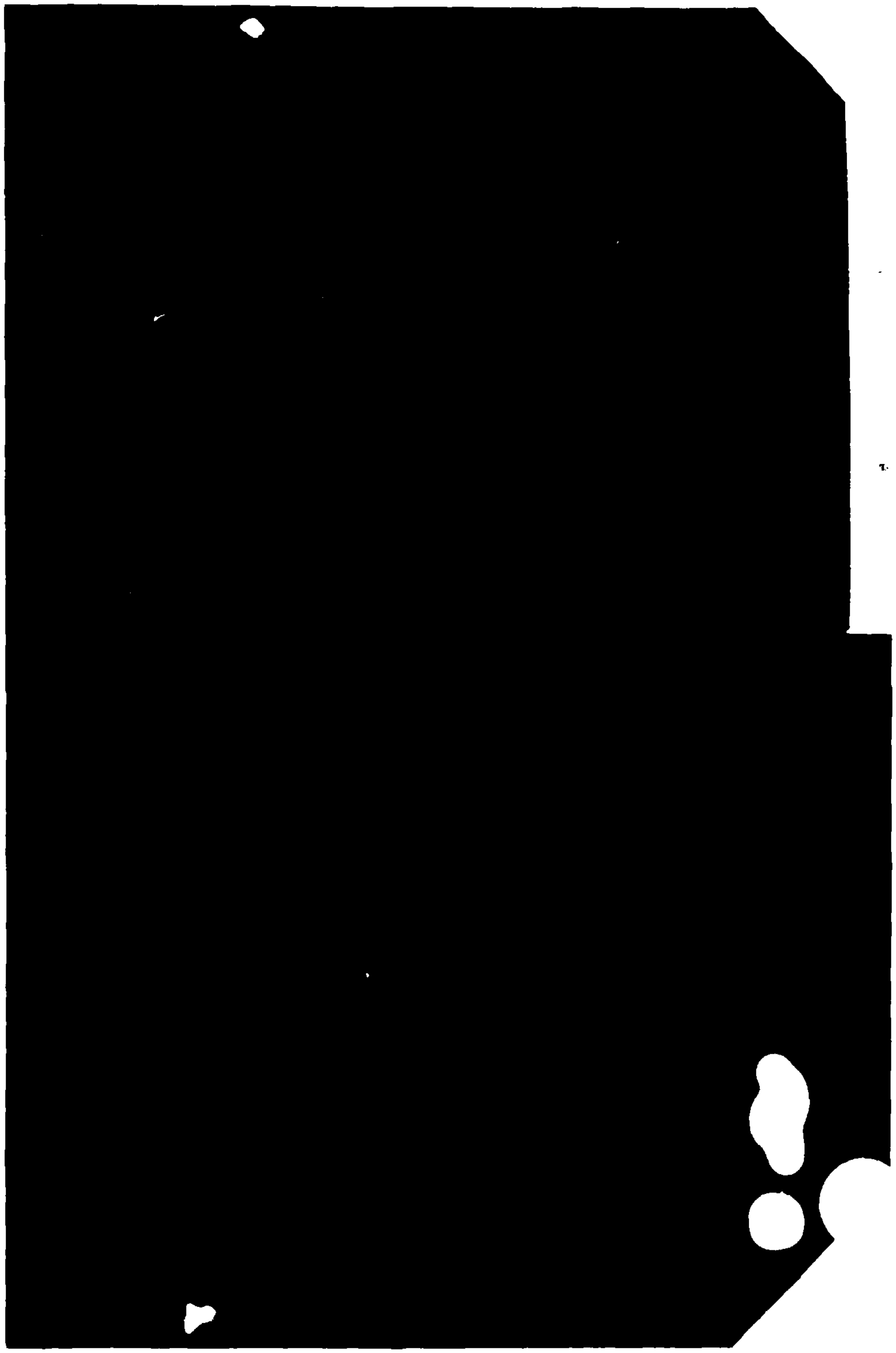

Figure 9. AFGL Triangulation photograph of Auroral E trail taken from CENTRAL site at 08:44 UT.

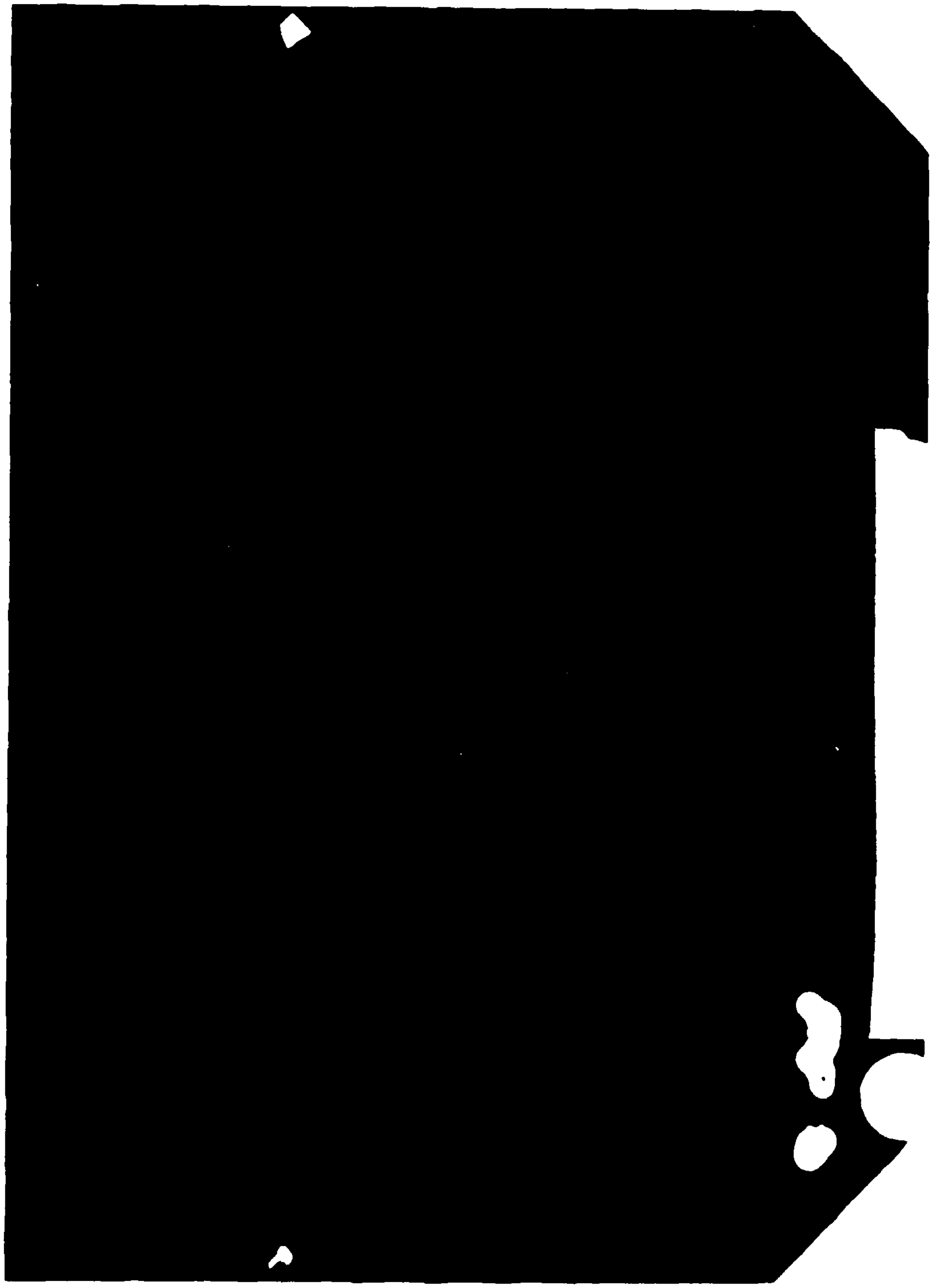

Figure 10. AFGL triangulation photography of Auroral E trail taken from CHENA site at 08:44 UT.

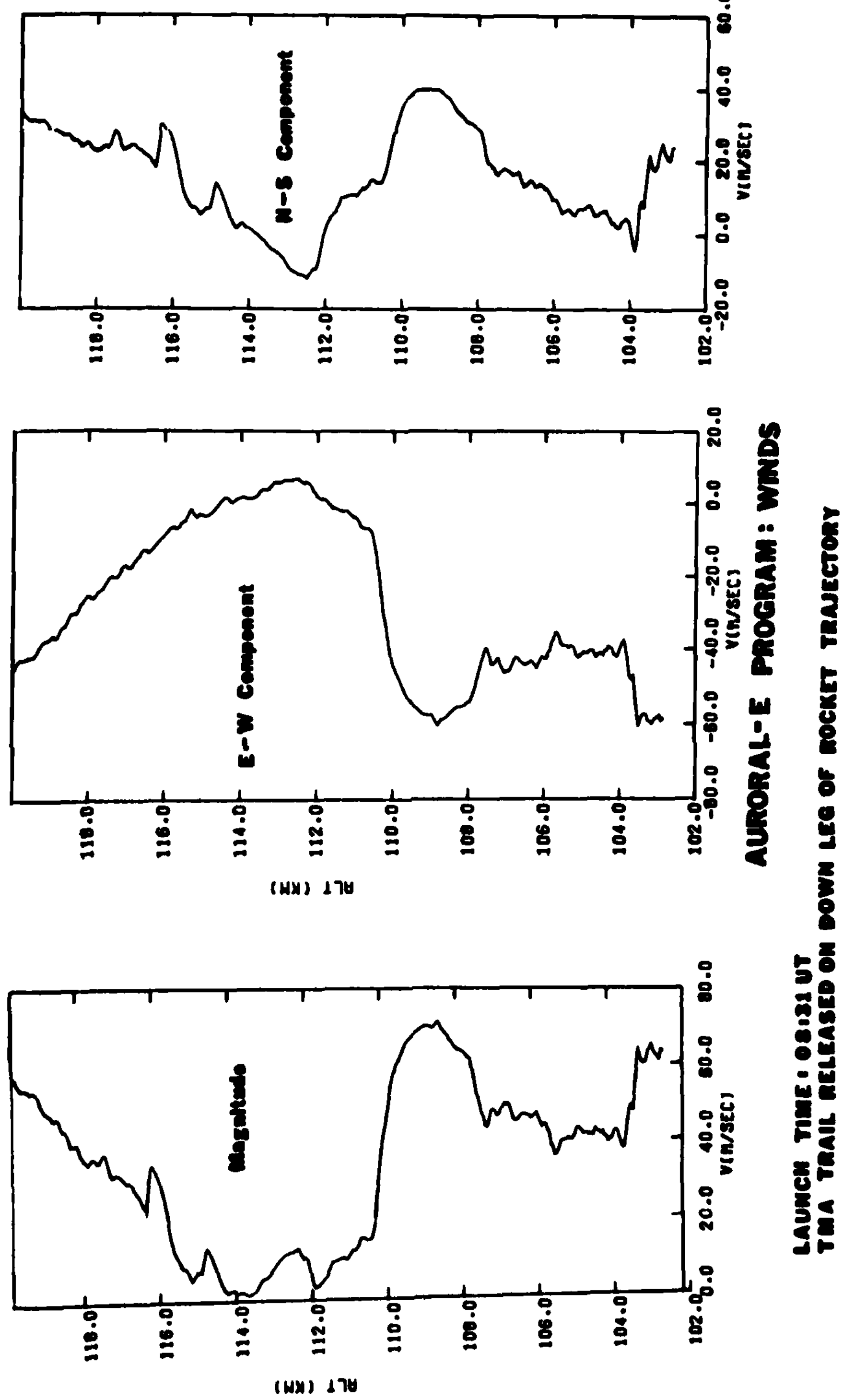

Figure 11. Horizontal winds reduced from the Auroral E trail, 102 to 120 km altitude.

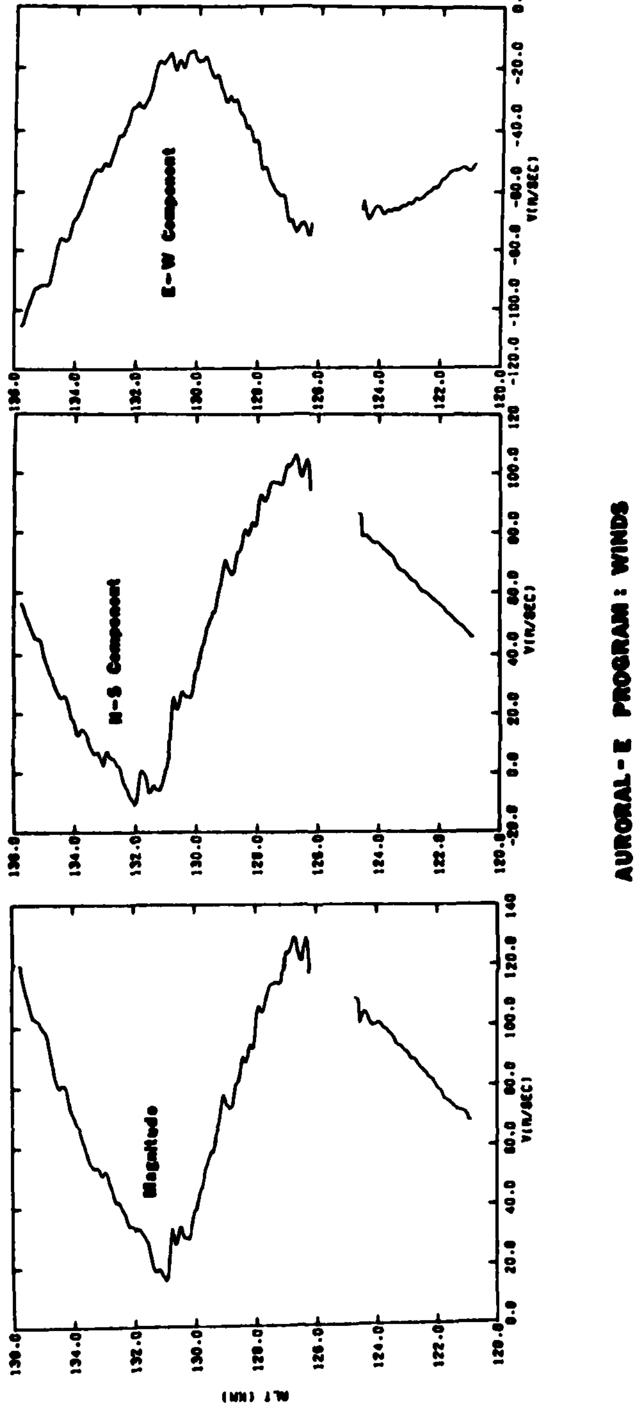

Figure 12. Horizontal winds reduced for the Auroral E trail, 120 to 138 km altitude.

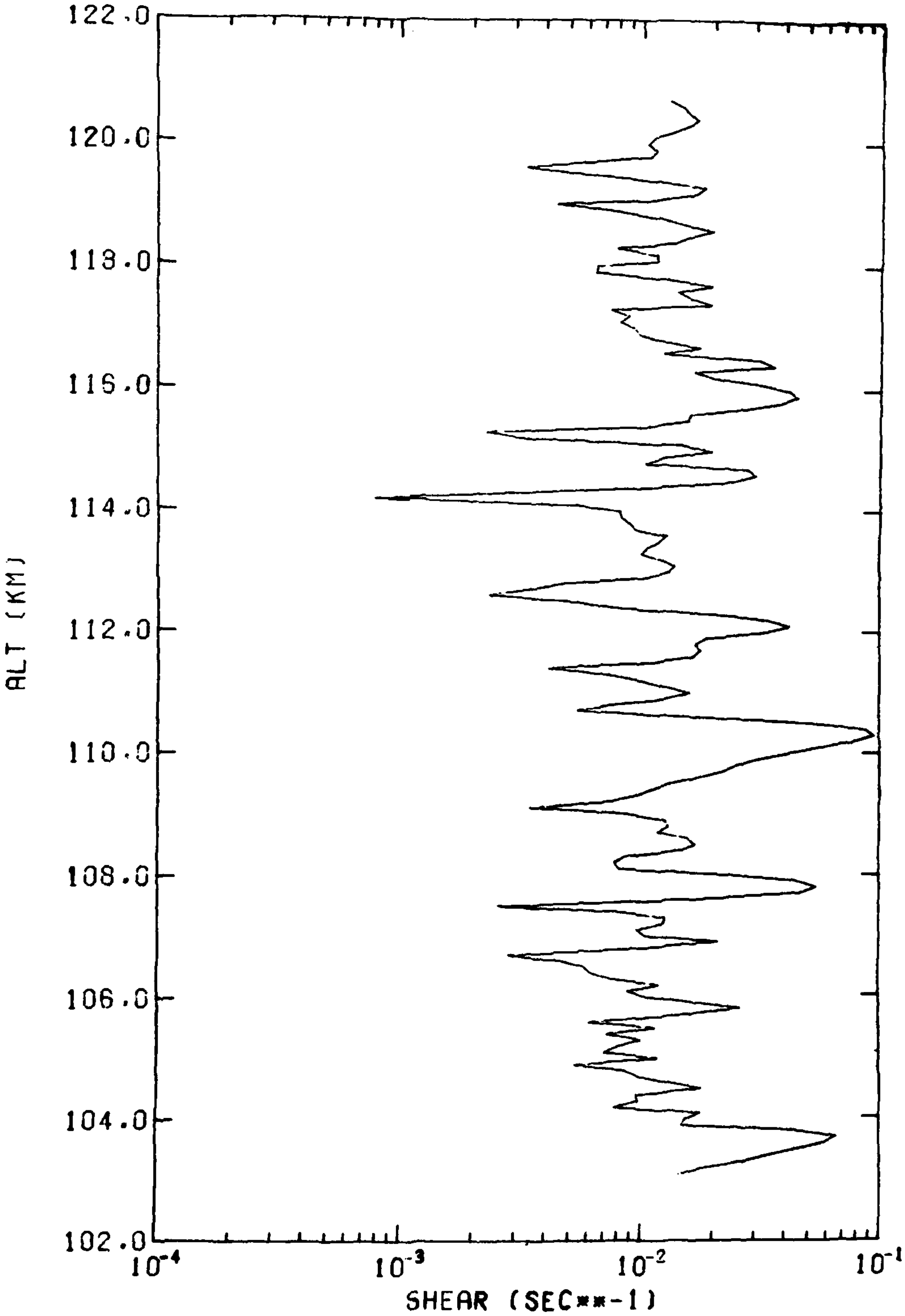

Figure 13. Profile of wind shear for the 102 to 120 km altitude region derived from Auroral E wind data.

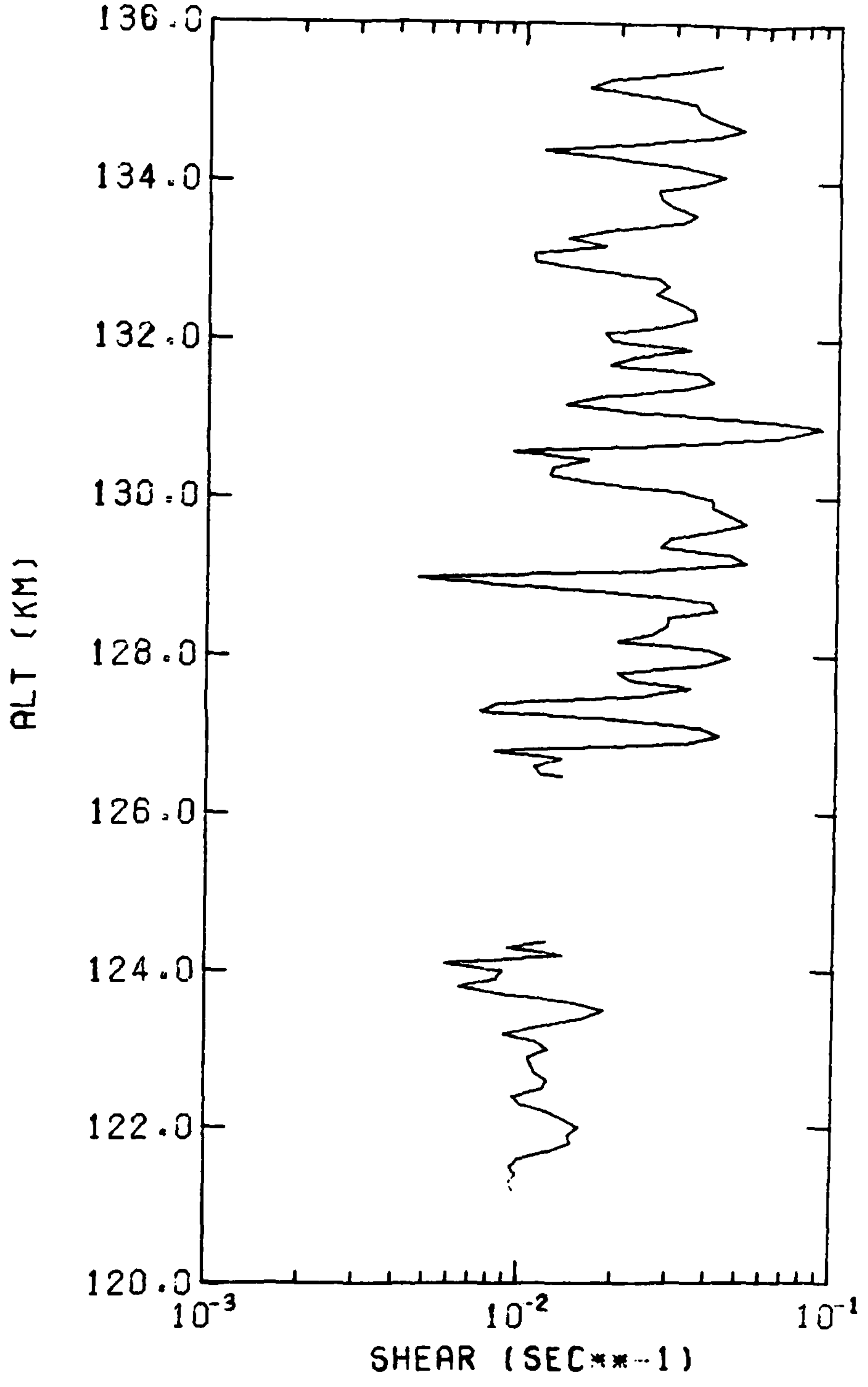

Figure 14. Profile of wind shear for the 120 to 138 km altitude region derived from Auroral E wind data.

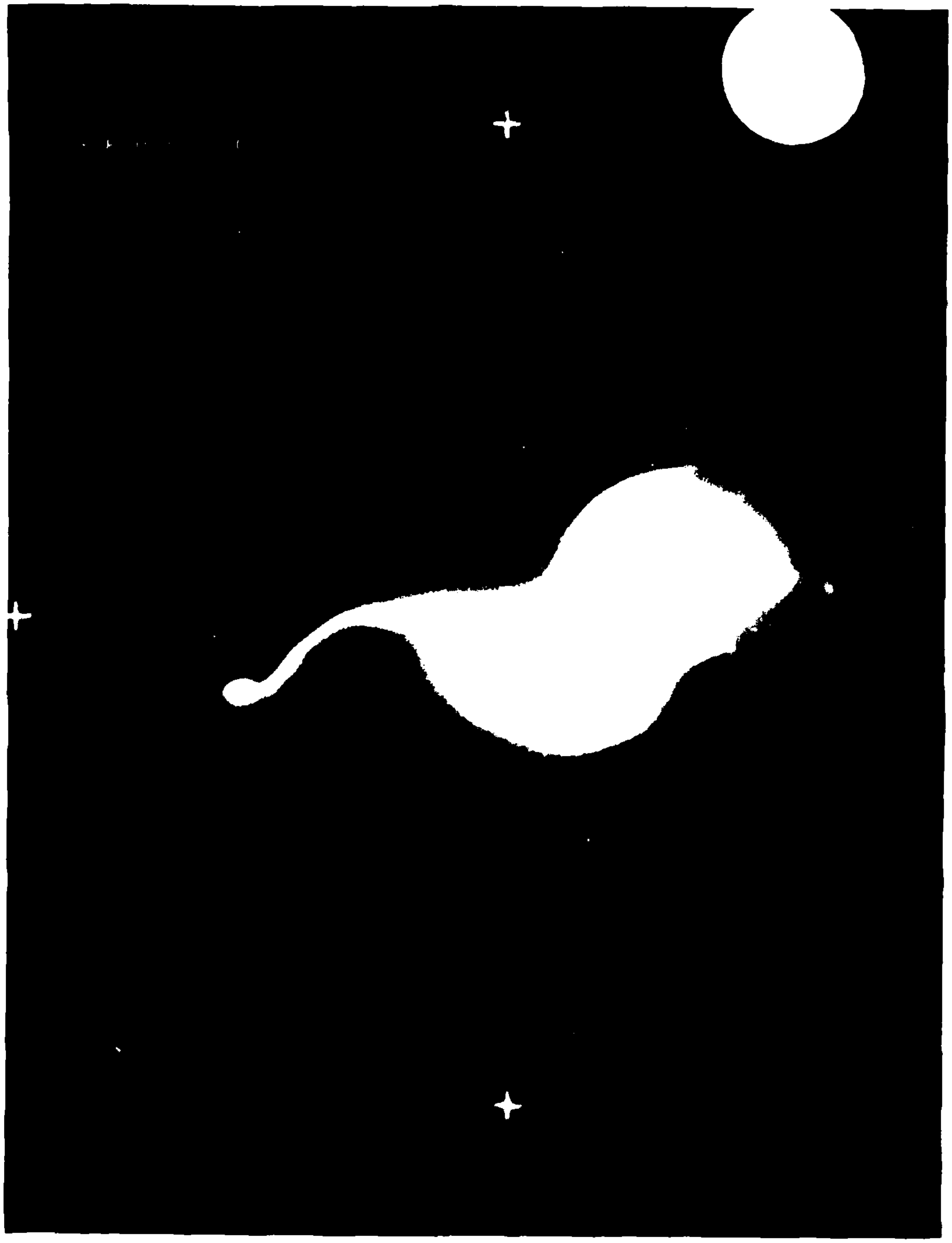

Figure 15. Auroral E trail at 08:44 UT photographed from POKER optical site by the University of Alaska. Note that the film is over-exposed from ~100 km downward.

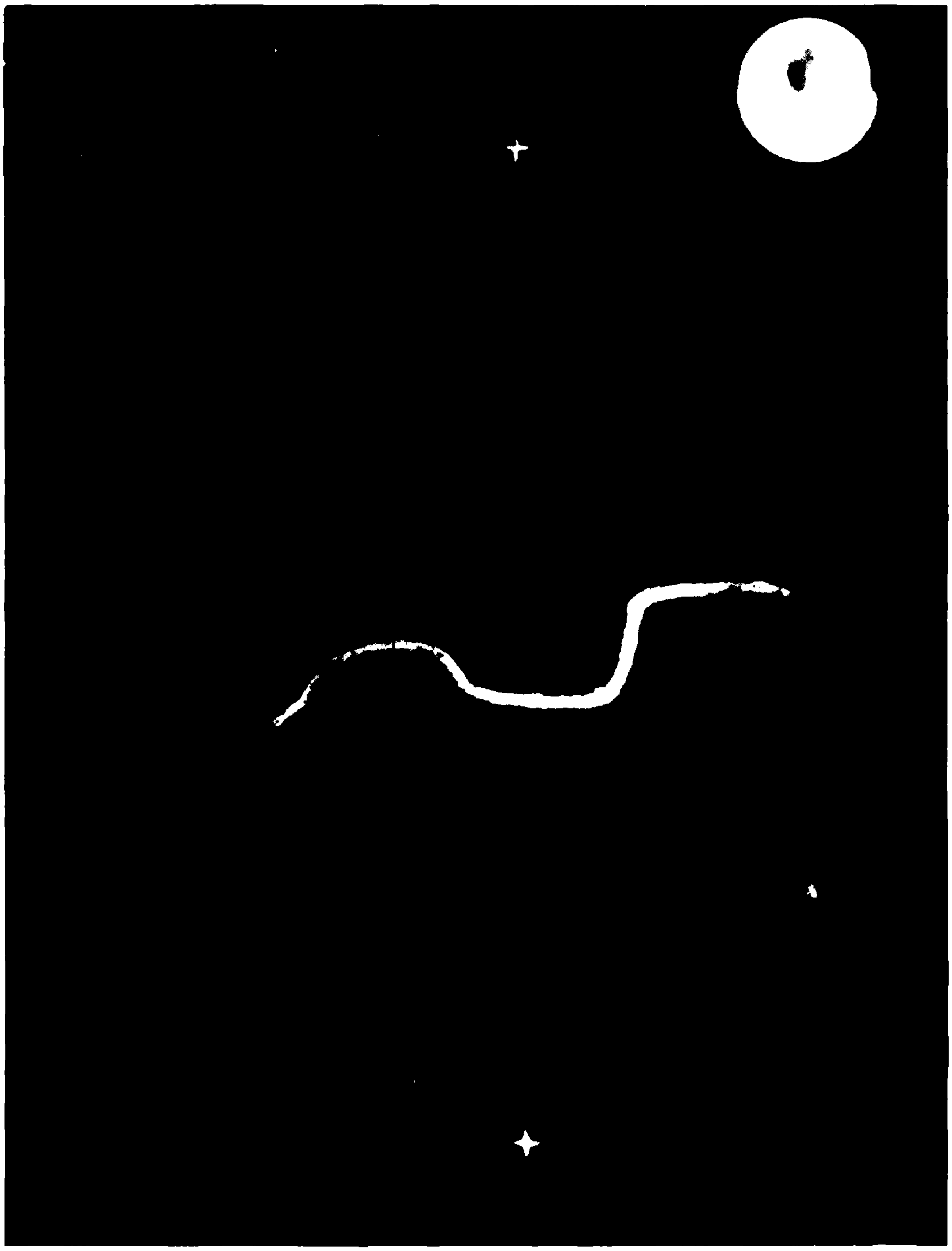

Figure 16. Enhanced version of Figure 16 used to digitize the initially low contrast "core" of the trail.

SECTION III

MODIFICATION AND MAINTENANCE OF THE TRAIL DIGITIZATION SYSTEM

At the start of the present program the existing computer and video film data processing equipment -- the Trail Digitization System -- was approximately 10 years old and the source of considerable lost time due to equipment failures. Much of the hardware was obsolete and repair parts were difficult or impossible to obtain. A major updating of both the computational and video segments, which would not only solve these breakdown problems but also greatly enhance the processing capability of the system, was therefore undertaken.

The Trail Digitization System as originally built was a major hardware and software modification of the AFGL's Video Densitometer System. All existing hardware was retained and a precision microprocessor controlled x-y stage was added to transport the film through the selected areas of the field of view of the video camera. Full field video imagery is suitable only for rough positioning of features (star images or center-lines of trails), while precise digital coordinates and densities or points on the film are obtained from encoded x and y axes of the stage.

Figure 17 is a block diagram of the new configuration of the Trail Digitization System. The 8K memory Datamate computer was replaced by a more powerful 32K memory Data General computer, the video disk memory by a Colorado Video solid state digital frame store, the magnetic tape unit by a faster and more reliable Data General unit, and the Teletype by a Data General terminal. A Data General Winchester disk drive was added to expand program and intermediate data storage, and in addition two smaller

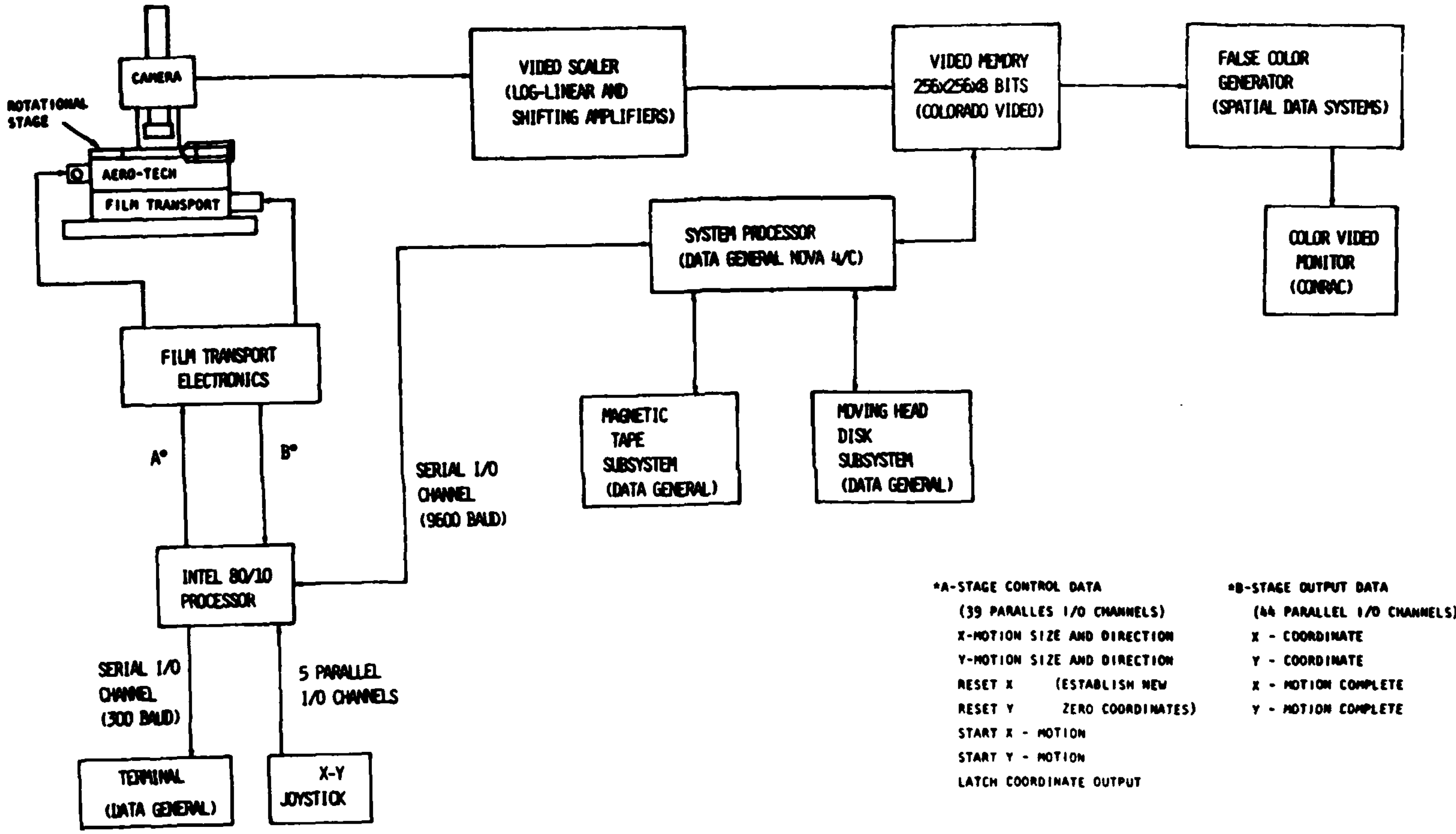

Figure 17. Block diagram of the Trail Digitization System after integration of the new hardware.

pieces of hardware, video sync stripper and video cross hair generator were incorporated. The sync stripper is used to provide necessary horizontal and vertical drive to the video camera and the cross hair generator places a visual reference on the video screen as an operator aid.

The video system is now synchronized totally electronically (previously synchronization was derived from the rotating video disk memory) which has eliminated a beat frequency problem between 60 Hz and the slightly off-60 Hz signal from the disk. Two incompatabilities of new and old equipment that arose were corrected. First the output voltage level of the AFGL Video Scaler was reduced from its 10V level to 1 volt for input to the new analog-to-digital converter, and the false color generator was similarly modified to operate at 1V level rather than 10V. Secondly, the digitize-and-store circuitry of the video memory was modified by addition of a separate video synchronization input and circuits to ensure that it would always digitize the same (geometric) video field.

The changes in hardware necessitated revision of large portions of the system software. The existing 16 Fortran programs were converted from the low level Datamate Fortran to Data General Fortran which allowed enhancement of much of the coding. Even though the overlay structure of the programs has been retained, a significant increase in system throughput has been achieved through expanded computer memory and shorter disk access time. The major processing speed advantage comes, however from a rewrite of the assembly language picture access and processing routines. These 25 subroutines were written to take advantage of the random access character of the new video memory (the old memory provided only video line by line access). The present maximum digitizing rate (hardware limit) is approximately 1200 coordinate pairs per hour. The average digitizing rate is about one half this figure, and is dependent upon the width of the trail image. The extreme slowness of diagonal or vertical trail scans using the old system (about 10 times slower than horizontal) has been eliminated.

Routine monthly preventive maintenance of the system has consisted primarily of cleaning system components that have moving parts (tape drive, data storage disk, dot matrix printer, and stage drives). Unscheduled maintenance has been performed when the television camera failed to perform adequately and could not be adjusted within specifications. After consulting the manufacturer, we returned the camera for overhaul; this included replacement of the vidicon tube. Several failures of the Data General terminal/printer have been repaired by Data General service personnel with average system down time of about four hours. Repairs have also been made to the only remaining older equipment, the AFGL video scaler and false color generator.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

An improved system for digitizing photographically recorded stratospheric tracer trail positions has been constructed. Digital positions have been acquired for several trails and high resolution horizontal wind vectors determined from these data. Routine calculations of horizontal stratospheric winds may be accomplished at vertical resolutions of less than 10 meters and standard deviations of velocity of approximately 0.2 m/sec.

Procedures for determining the orientation of the triangulation cameras have been simplified through the addition of a digital star catalog to the analysis system. Most of the previous manual effort in digitizing star coordinates -- locating and identifying from charts each star image on the film, moving the stage to center the image in the video field of view, and entering the star's right ascension and declination -- has been automated. The accuracy of digitizing the star coordinates has been increased from approximately 20μm to approximately $\pm 8\mu$m. Camera pointing or orientation uncertainties are routinely better than 0.005° and lens focal length determination better than 50μm.

Further analysis of the wind data was routinely performed to determine the vertical shear of the horizontal wind, which is a description of the degree of turbulence present. The Richardson number which is a further descriptor of atmosperic turbulence, was calculated for two trails for which an altitude profile of stratospheric temperature was available.

The smoke trail technique was applied successfully to a high altitude sunlight-scattering chemical trail and could thus be used as a calibration procedure for high altitude radar wind measurements (such as those made by the MST radar).

The dashed trail technique, which evolved several years ago as a means of providing identifiable points on the trail (dash ends), should be reconsidered in favor of continuously relased smoke since the triangulation no longer requires these markers. Continuous trails would allow a full profile of horizontal wind velocity as a function of altitude (approximately one third to one half of the data are now lost in the gaps between dashes).

With the integration of the new hardware into the Trail Digitization System, maintenance requirements have decreased significantly. Failures have been limited to devices which have mechanical parts and to the remaining old electronic equipment. Digitizing efficiency has been increased through the reduction of time spent in troubleshooting and repair of the system.

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